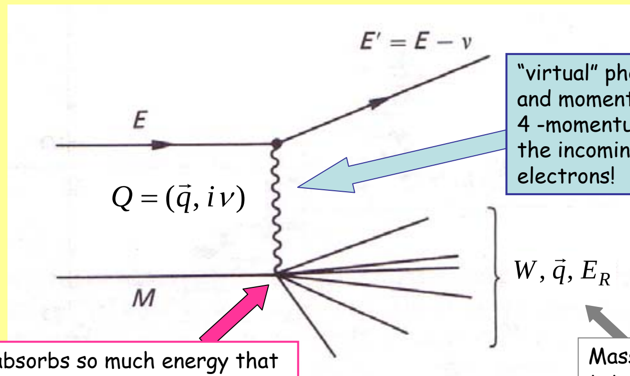
16.451 Lecture 11: Quarks inside the proton *Oct. 13, 2005* 1

Idea: try to identify a kinematic regime in which the electrons scatter from pointlike constituents inside the proton: **"deep inelastic scattering"**

Microscopic scattering mechanism:

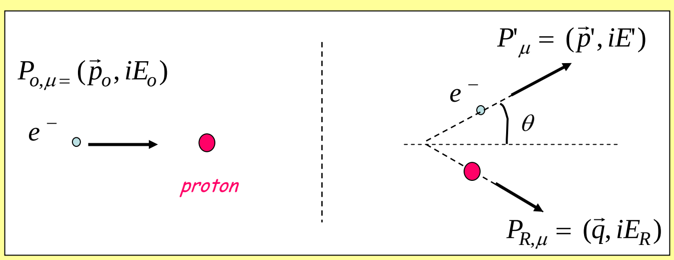


"virtual" photon has energy and momentum given by the 4 -momentum transfer from the incoming & outgoing electrons!

proton absorbs so much energy that the intermediate excited state flies apart very quickly afterwards.

Mass, momentum, and total energy of the recoiling object after the collision

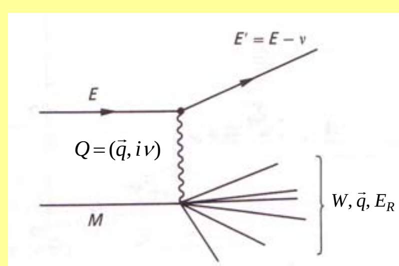
Kinematic analysis: 2



Note new definitions:

for consistency with high energy textbooks, the symbol W represents the mass of the recoiling object, and ν is the energy transferred by the electron.

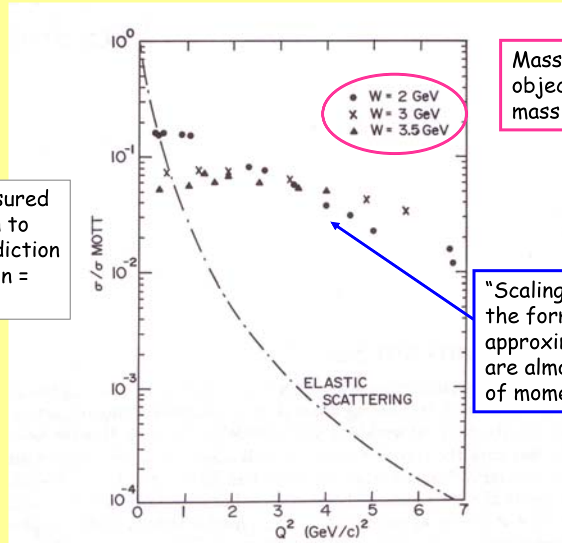
(careful: $\nu \neq E_R$ because of the mass terms...)



$$Q = (P_o - P') = \left(\vec{p}_o - \vec{p}',\ i\,(E_o - E')\right) \equiv \left(\vec{q},\ i\,\nu\right)$$

First discovery: for large energy transfer, the form factors are independent of Q^2 3

M. Breidenbach et al., Phys. Rev. Lett. 23, 935 (1969)

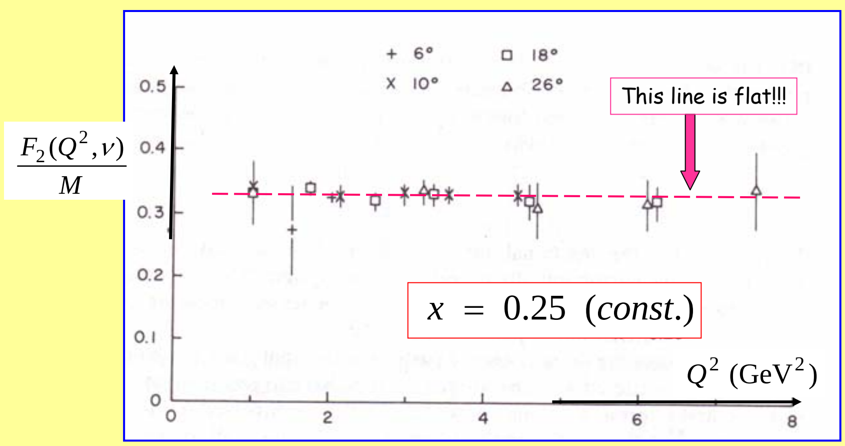


Ratio of measured cross-section to pointlike prediction for the proton = form factor!

Mass of recoiling object is 2 – 3 x the mass of the proton!

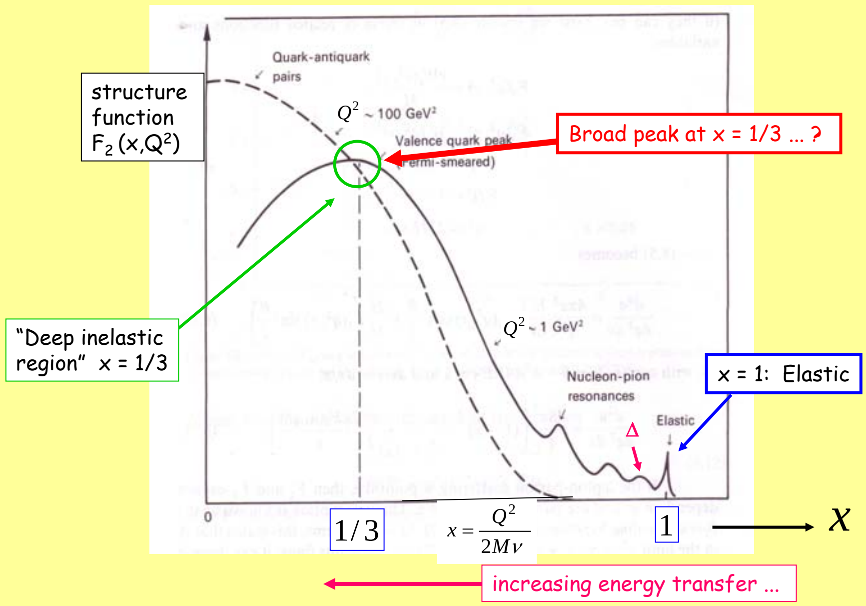
"Scaling" – in this regime, the form factors are approximately equal and are almost independent of momentum transfer…

Evidence of point-like quarks comes from "scaling" of the structure functions 4

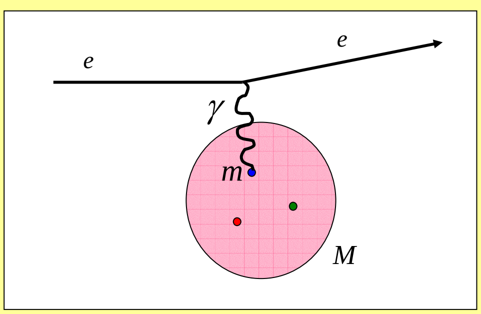


Idea: pointlike scattering object has a constant form factor or structure function. The proton structure functions are essentially independent of Q^2 in the deep inelastic regime, indicating scattering from pointlike constituents with mass approx 1/3 the proton mass $\rightarrow$ u and d quarks!

Look again at the features in x: 5



Scattering from quarks? 6



Elastic scattering from the proton is a **narrow** peak at x = 1

Deep inelastic scattering shows a **broad** peak at x = 1/3 ... ???

- If the quark has mass m = M/3, then we should see a peak at:

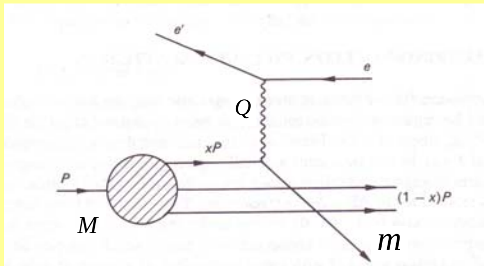
$$\frac{Q^2}{2m\nu} = 1 \quad \Rightarrow \quad x = \frac{Q^2}{2m\nu} \times \frac{m}{M} = \frac{1}{3}$$

- The peak is broad because the quark is confined in a small space – the quark `target' is moving in a random direction inside the proton *(very fast!!!)*

Estimate: $\Delta p\, \Delta x \approx \hbar \Rightarrow c\Delta p \approx \frac{\hbar c}{\Delta x} = \frac{197 \text{ MeV fm}}{0.8 \text{ fm}} = 250 \text{ MeV} \sim mc^2$!!

A bit more about "x" 7

Feynman's "parton" model, 1969: viewed in a frame in which the proton is moving relativistically, deep inelastic scattering **(DIS)** involves the electron scattering from a single "parton" with a **fraction x of the proton's total momentum**.



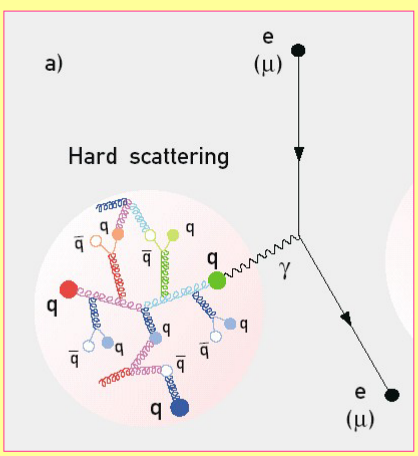
$$x = \frac{Q^2}{2M\nu} = \frac{m}{M}$$

Comparing DIS structure functions for different targets (n, p, ^{3}He, etc...) allows the individual quark and anti-quark distribution functions to be mapped out, ie, we can measure what fraction of the proton's momentum is carried by each kind of quark.

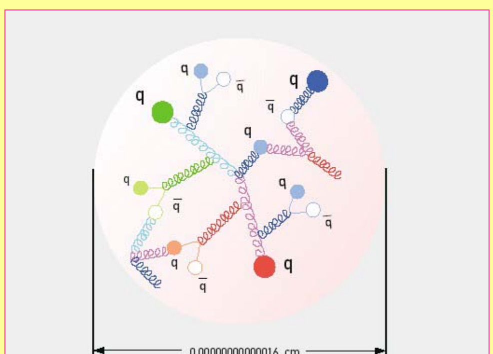
Observations:
1. only about 60% of the proton's momentum is carried by quarks
2. only about 30% of the proton's spin is due to the quarks

... so what else is in there ????

We don't know exactly, but there is a great deal of effort underway to find out! 8



Have another look at the NSAC long range plan (web link, lecture 1.) p.14 – 28 –you should be able to understand a lot more of it now!!!



Inside the nucleon. Within the theory of QCD, the nucleon has a complex internal structure, consisting of three valence quarks (large dots), which are continually interacting by the exchange of gluons (depicted as springs in this schematic picture). In contrast to the photons that are exchanged between electric charges, gluons interact not only with the valence quarks, but also with each other, creating and destroying gluons and quark-antiquark pairs (small dots).

(N.B. scattering at **very** small x is sensitive to the presence of **anti-quarks** inside the proton – these are important too! (research frontier)...

Nobel Prize 2004

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The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

David J. Gross	H. David Politzer	Frank Wilczek
1/3 of the prize	1/3 of the prize	1/3 of the prize
USA	USA	USA
Kavli Institute for Theoretical Physics, University of California Santa Barbara, CA, USA	California Institute of Technology Pasadena, CA, USA	Massachusetts Institute of Technology (MIT) Cambridge, MA, USA
b. 1941	b. 1949	b. 1951

David Gross, **David Politzer** and **Frank Wilczek** have made an important theoretical discovery concerning the strong force, or the 'colour force' as it is also called. The strong force is the one that is dominant in the atomic nucleus, acting between the quarks inside the proton and the neutron. What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called "asymptotic freedom". The converse is true when the quarks move apart: the force becomes stronger when the distance increases. This property may be compared to a rubber band. The more the band is stretched, the stronger the force.

This discovery was expressed in 1973 in an elegant mathematical framework that led to a completely new theory, *Quantum ChromoDynamics*, QCD. This theory was an important contribution to the Standard Model, the theory that describes all physics connected with the electromagnetic force (which acts between charged particles), the weak force (which is important for the sun's energy production) and the strong force (which acts between quarks). With the aid of QCD physicists can at last explain why quarks only behave as free particles at extremely high energies. In the proton and the neutron they always occur in triplets.

"Running" of Coupling Constants with energy scale is a key prediction

Running Coupling Constants:

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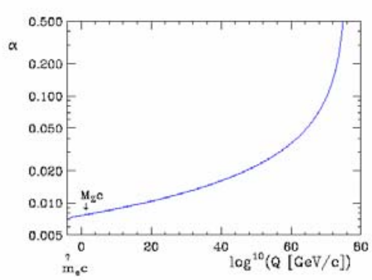
Fine structure constant: $\alpha = \dfrac{e^2}{4\pi\epsilon_0 \hbar c} = \dfrac{1}{137.035\,999\,76\,(50)} = 0.007\,297\,352\,533\,(27)$

But, measurements at high energies (LEP at CERN): $\alpha \simeq \dfrac{1}{128} \simeq 0.00781$

(in agreement with theory)

What is going on? α is *not* constant but "energy"-dependent (more precisely momentum-transfer Q [E/c])

Extrapolating to higher energies using quantum electrodynamics (QED) α becomes infinitely large – "the Landau pole"



Why is the fine structure constant (coupling) behaving this way?

Energy dependent coupling constants – a quantum mechanical reality, J. Rathsman, ISV 2003-12-09 2

Excerpt from lecture by J. Rathsman, Univ. of Uppsala, Sweden

Ref: http://www3.tsl.uu.se/~rathsman/docent.pdf

Quantum Electrodynamics:

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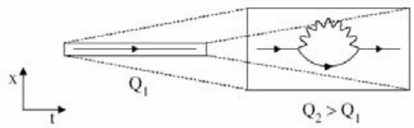
Describes the interactions of electrically charged particles mediated by photons

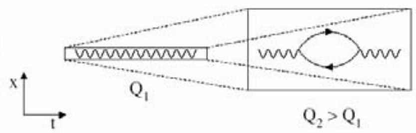
Main differences to classical electrodynamics: uncertainty principle $\Delta x \Delta p \geq \hbar$ and quantisation of fields (photons) $\Rightarrow$ the number of particles is *not* constant

Increasing the resolution $Q \sim \hbar/\Delta x$ we resolve quantum fluctuations

electron:



photon:



Vacuum Polarization in QED

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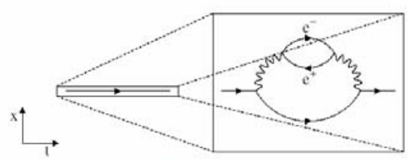
Combining these two types of fluctuations will polarise the vacuum around an electron

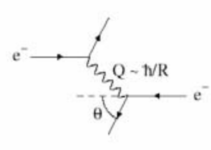


Increasing the resolution $Q \sim \hbar/\Delta x \Rightarrow$ what we thought was one charge is actually fluctuating into several

How can this be observed? (Why should we care about quantum fluctuations?)

to probe short distances $R \sim \Delta x$ we need processes with large momentum-transfers $Q \sim \hbar/R$

for example by scattering two high energy electrons to large angle ($Q = 2E \sin\frac{\theta}{2}/c$)



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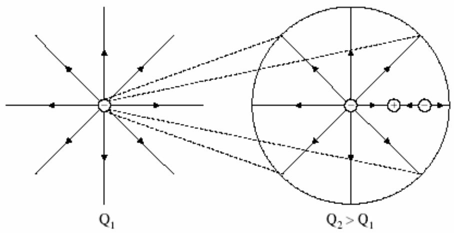
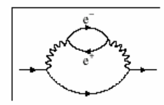
The electric field (at distance $R \sim \hbar/Q$) from an electron in vacuum: $|\vec{E}| = \dfrac{e(R)}{4\pi\varepsilon_0 R^2}$





Quantum fluctuations polarise the vacuum and *screen* the charge at large distances cf. dielectric medium with $\varepsilon(R) > \varepsilon_0$, $\left(|\vec{E}| = \dfrac{e(R)}{4\pi\varepsilon_0 R^2} \leftrightarrow \dfrac{e}{4\pi\varepsilon(R) R^2} \right)$

Decreasing R the electric field increases faster than $1/R^2$
$\Rightarrow$ the magnitude of the charge has increased

Limits: $\begin{cases} R \to \infty \; (Q \to 0) \Rightarrow e \to -1.602\,176\,462(63) \cdot 10^{-19} C \\ R \to 0 \; (Q \to \infty) \Rightarrow e \to -\infty \quad \text{("bare charge", cf. the Landau pole)} \end{cases}$

Running of the Strong coupling constant:

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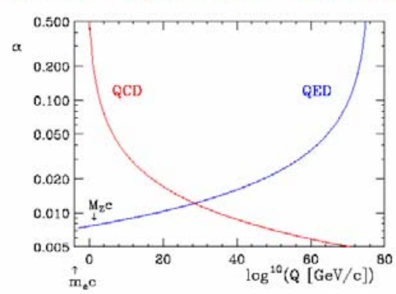
In the sixties Gell-Mann and Zweig showed how hadrons (e.g. protons and neutrons) can be understood as composite states of quarks – are quarks real or mathematical?

1. As the name implies the strong interaction is strong – the coupling is large at small energies
2. To be able to describe the strong interaction using quarks the coupling has to be small



1973: Gross & Wilczek and Politzer ('t Hooft) showed that the strong coupling decreases as the energy is increased (birth of quantum chromodynamics (QCD), the theory of strong interactions)

$\Rightarrow$ quarks are real (not mathematical), possible to make precise calculations also in strong interactions at large momentum-transfers (asymptotic freedom)

Experimental evidence for "asymptotic freedom" in QCD is convincing:

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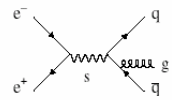
Asymptotic freedom

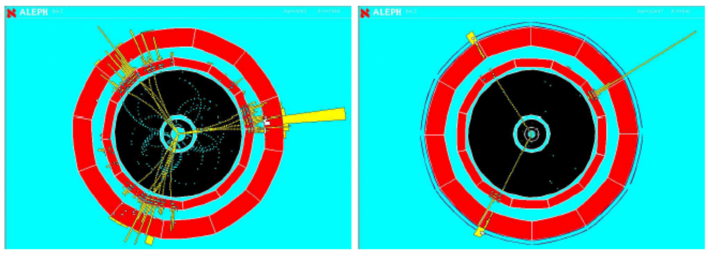
The coupling α_s is small for large momentum-transfers ($Q^2 \gtrsim 1$ GeV^2)
$\Rightarrow$ perturbative expansion in α_s possible, $\sigma = \sum_n \sigma_n \alpha_s^n$

Can make calculations with quarks and gluons as if they where free particles

Ex. Three-jet events: $e^+e^- \to q\bar{q}g$
similar structure as $e^+e^- \to \mu^+\mu^-\gamma$
(discovery of gluon at DESY in 1979)



$$\alpha_s \simeq \frac{\sigma_{3-\text{jets}}}{\sigma_{\text{had}}}$$



Running of the Strong coupling constant, α_s

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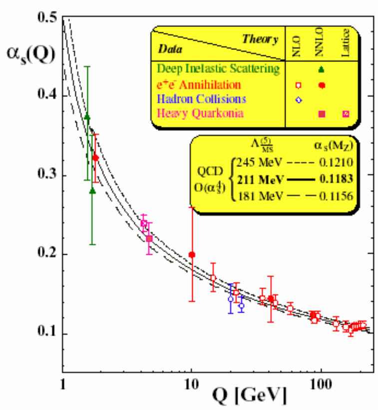
Experimental data and theory



Evolution equation for coupling (leading order, QED and QCD)

$$\frac{d\alpha(Q^2)}{d\ln Q^2} = \beta\alpha(Q^2)^2$$

sign of $\beta \Rightarrow$ increase or decrease
($\beta_{\text{QCD}} = \frac{2N_F-33}{12\pi}$, $\beta_{\text{QED}} = \frac{N_{\text{gen}}}{3\pi}$)

Solution

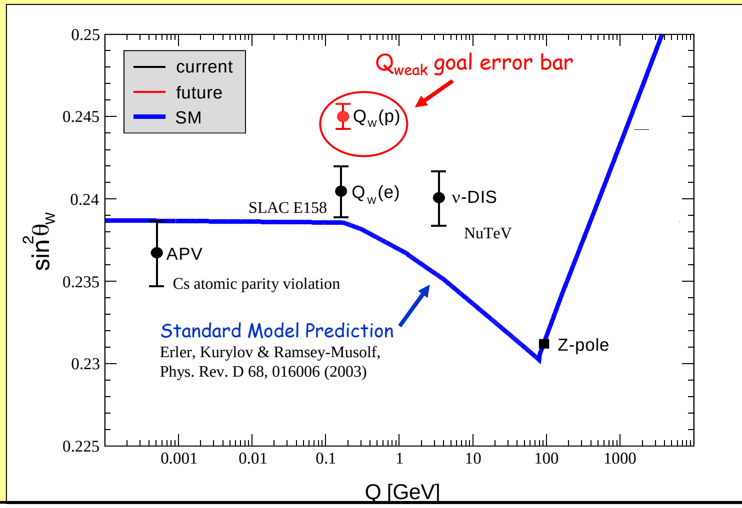
$$\alpha(Q^2) = \frac{1}{-\beta\ln(Q^2/\Lambda^2)}$$

Λ small in QCD (large in QED)

Shows running of coupling in agreement with theory, $\mathcal{O}(\alpha_s^4)$!

Running of the weak interaction with energy scale: http://www.jlab.org/qweak/ 17

The 'weak mixing angle', $\sin^2\theta_W$, sets the scale of the weak interaction between particles. Our group plays a major role in the "Q_{weak}" experiment at Jefferson Lab to measure the weak charge of the proton: $Q_w(p) = 1 - 4\sin^2\theta_W$ in order to test the running of the weak interaction with energy scale. Only a handful of measurements exist, and it is not yet clear whether the Standard Model predictions are confirmed in this case. (60 collab., total cost US$4M, to take data in 2008)

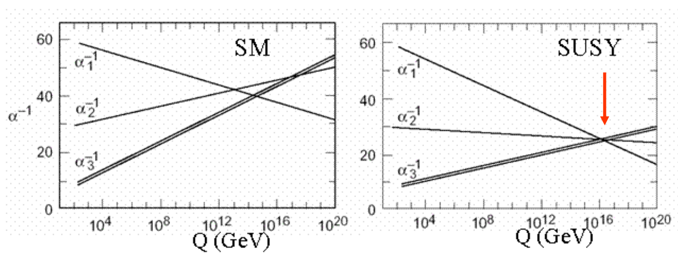


Unification of Forces? 18

Unification of Strong, Electromagnetic and Weak Forces?

Grand Unified Theories (GUTs)

In the 1800's, the phenomena of electricity and magnetism were demonstrated to be two aspects of a unified electromagnetic force. This was a spectacular achievement and is well described theoretically by Maxwell's equations and quantum electrodynamics. In the 1960's and 1970's, a similarly spectacular achievement was the demonstration that electromagnetic and weak interactions are two aspects of a unified electroweak force. Many believe that there should also be unification of the strong and electroweak forces, described by a Grand Unified Theory (GUT) at a very high energy scale of ~10^{16} GeV. At even higher energy, at the Planck scale of 10^{19} GeV, a quantum theory of gravity might lead to a further unification of all 4 forces. GUT theories require that the running strengths of the Strong, Electromagnetic and Weak forces become the same at the GUT energy scale. The Standard Model makes precise predictions for these running strengths, plotted below for α_1, α_2 and α_3; these coupling constants are related to the electromagnetic coupling constant, weak mixing angle and strong coupling constant by the relations given below (see also Peskin reference). As seen in this figure, the running strengths for the 3 forces never coincide. However, if one makes the same plot for a supersymmetric (SUSY) extension of the Standard Model, one does find an energy scale with unified couplings! But does SUSY really exist?? It postulates a doubling of the known particles, with a SUSY counterpart to the electron called a selectron for example. Stable SUSY particles may also be responsible for the large abundance of Dark Matter in the Universe. Experiments at CERN's Large Hadron Collider (LHC) and the proposed International Linear Collider will tell us in the coming decade if nature is supersymmetric..



$$\alpha_1 = \frac{5}{3}\cdot\frac{\alpha_{EM}}{\cos^2\theta_W}$$

$$\alpha_2 = \frac{\alpha_{EM}}{\sin^2\theta_W}$$

$$\alpha_3 = \alpha_S$$

http://www-project.slac.stanford.edu/e158/running-unification.html

Supersymmetry: http://www.superstringtheory.com/experm/exper4.html 19

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One of the predictions of string theory is that at higher energy scales we should start to see evidence of a symmetry that gives every particle that transmits a force (a boson) a partner particle that makes up matter (a fermion), and vice versa.

This symmetry between forces and matter is called **supersymmetry**. The partner particles are called **superpartners**.

Known particles that transmit forces, and their possible superpartners

Name	Spin	Superpartner	Spin
Graviton	2	Gravitino	3/2
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
$W^{+,-}$	1	$\text{Wino}^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

Known particles that make up matter, and their possible superpartners

Name	Spin	Superpartner	Spin
Electron	1/2	Selectron	0
Muon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

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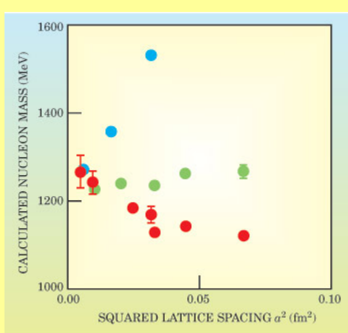
What about QCD at low energy scales? 20

Numerical simulations on a discrete space point lattice – so-called "lattice QCD" calculations are used to try and predict e.g. baryon mass spectra in the regime where the strong coupling constant is too large to solve the equations directly.

→ Issue is to extrapolate to zero lattice spacing, i.e. reality.

Ref: "Lattice QCD Comes of Age", de Tar & Gotlieb, Physics Today, 2004: http://www.physicstoday.org/pt/vol-57/iss-2/p45.html



"Calculated nucleon mass as a function of lattice spacing a for a variety of lattice quark-action algorithms. The smaller the slope, the better the algorithm. The blue points indicate results with the unimproved staggered-fermion action devised in 1976 and used well into the 1990s. The red points indicate an improved version of Kenneth Wilson's original quark action used in the late 1990s. The ISF action, represented by the green points, clearly shows the least dependence on lattice spacing. The nucleon mass, in the limit of vanishing a, comes out about 300 MeV too high because all these calculations, for simplicity of comparison, used unphysically high u and d masses and ignored quark-loop effects."